Quantitative Comparison of Electromagnetic Performance of Electrical Machines for HEVs/EVs

Z. Q. Zhu, *Fellow, Royal Academy of Engineering,* W. Q. Chu, and Y. Guan

(Invited)

***Abstract*—In this paper, various types of sinusoidal-fed electrical machines, i.e. induction machines (IMs), permanent magnet (PM) machines, synchronous reluctance machines, variable flux machines, wound field machines, are comprehensively reviewed in terms of basic features, merits and demerits, and compared for HEV/EV traction applications. Their latest developments are highlighted while their electromagnetic performance are quantitatively compared based on the same specification as the Prius 2010 interior PM (IPM) machine, including the torque/power-speed characteristics, power factor, efficiency map, and drive cycle based overall efficiency. It is found that PM-assisted synchronous reluctance machines are the most promising alternatives to IPM machines with lower cost and potentially higher overall efficiency. Although IMs are cheaper and have better overload capability, they exhibit lower efficiency and power factor. Other electrical machines, such as synchronous reluctance machines, wound field machines, as well as many other newly developed machines, are currently less attractive due to lower torque density and efficiency.**

***Index Terms*—Electrical machines, electric vehicles, hybrid electric vehicles, induction machines, permanent magnet machines, switched reluctance machines, synchronous reluctance machines, variable flux machines, wound field machines.**

I. INTRODUCTION

ELECTRIC vehicles (EVs) have been widely recognized as the future of transportation. In the last decades, both hybrid EVs (HEVs) and pure EVs have attracted increasing attention and grown rapidly [1, 2]. The electric propulsion system is the heart of HEVs/EVs, while the electrical machines are the core component of the electric propulsion systems.

On the other hand, progress of materials, power electronics, and control technologies has enabled the developments of various electrical machines. In order to guide the selection and design of electrical machines for HEV/EV traction applications, it is necessary to review and compare various electrical machines against the relevant requirements.

Existing comparative literature on different types of electrical machines for HEV/EV traction applications can be divided into two groups. The first group is review papers which can be found in [3-15]. These review papers very often cover most of the conventional electrical machines. However, the review and comparison are based on general features and hence qualitative only. The secondary group is comparative investigations based on quantitative performance. In [16], an induction machine (IM) and a switched reluctance (SR) machine are designed and compared with the Prius 2004 interior permanent magnet (IPM) machine. In [17], SR machines are developed and compared with the Prius 2003 IPM machine. However, the comparison in [16] and [17] only covers a few selected operation conditions. In [18], an IM with aluminium rotor is designed and compared with an IPM and surface-mounted PM (SPM) machines for a 50kW traction application at the same stack dimensions and inverter size. In [19], the comparison is carried out between the IM with copper rotor and the Prius 2004 IPM machine. The comparative studies in [18] and [19] are extended to consider the efficiency maps as well as the drive cycle based performance. However, the investigations in [16-19] only cover selected two or three types of electrical machines in each paper and do not include synchronous reluctance and PM-assisted synchronous reluctance machines which currently are one of the hot research directions. The benchmark IPM machines of these papers are designed a decade ago, and thus the existing comparisons are less useful on highlighting the developing trends.

In this paper, much more comprehensive and quantitative comparison is conducted amongst all types of feasible sinusoidal-fed electrical machines based on the same traction specification. With the major requirements of HEV/EV traction highlighted, various electrical machines are briefly reviewed. The most feasible six types of electrical machines are selected for quantitative comparison. Since Prius is the most popular HEV, its later design (i.e. Prius 2010 IPM machine) are used as the benchmark and shared specification. Following the individual review and comparison with the Prius 2010 IPM machine, the most promising four types of electrical machines are further synthetically compared in terms of torque-speed curves, power factor, efficiency maps, and overall efficiencies

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Professor Z Q. Zhu is with the Fellow of Royal Academy of Engineering, Fellow IEEE, Fellow IET, PhD, Professor at The University of Sheffield, UK.(e-mail: Z.Q.Zhu@Sheffield.ac.uk) (Corresponding author)

Dr W Q. Chu is with the University of Sheffield, UK. (e-mail: chu.wenqiang@gmail.com).

Dr Y. Guan is with the University of Sheffield. (e-mail: ggreetyy@gmail.com).

for different drive cycles. The conclusions are highlighted afterwards.

II. Major Requirements for HEV/EV Traction Machines

Since electric propulsion system is the heart of HEV/sEVs, the benefits and advanced performance of HEVs/EVs are largely determined by the relevant electric propulsion systems. The major requirements of the EV electrical machines are summarized as follows [3]: (a) High torque density and power density; (b) High torque for starting, at low speeds and hill climbing, and high power for high-speed cruising; (c) Wide speed range, with a constant power operating range of around 3–4 times the base speed; (d) High efficiency over wide speed and torque ranges, particularly at low torque operation; (e) Intermittent overload capability for short durations; (f) High reliability and robustness appropriate to the vehicle environment; (g) Acceptable cost; (h) Low acoustic noise and low torque ripple are important design considerations. These requirements will serve as the guidelines to review and select different types of electrical machines for HEV/EV tractions.

III. Overview of Electrical Machines

Various electrical machines have been developed over the past few decades with the help of progress on materials, power electronics, and control technologies. The major electrical machine technologies are summarized in Fig. 1 and illustrated in Fig. 2.

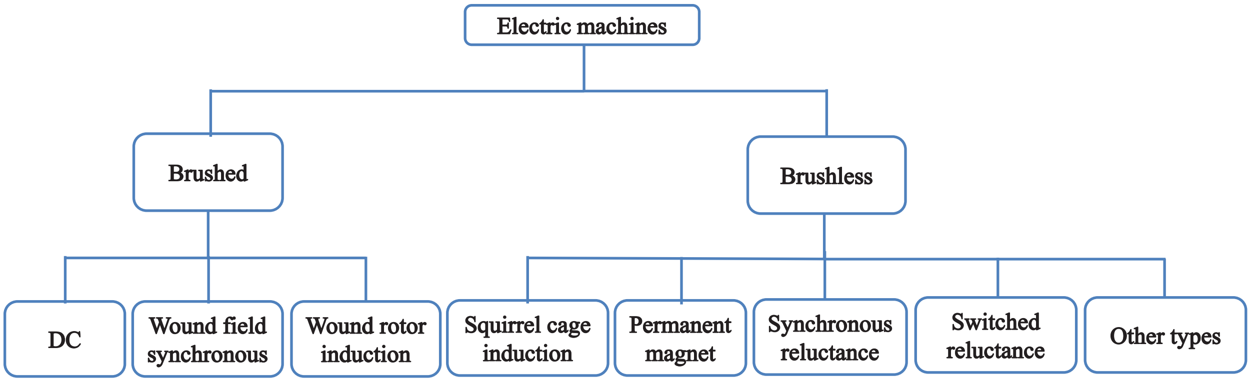
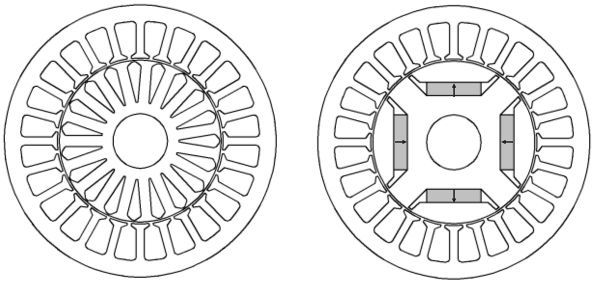


Fig. 1. Major electrical machine technologies.

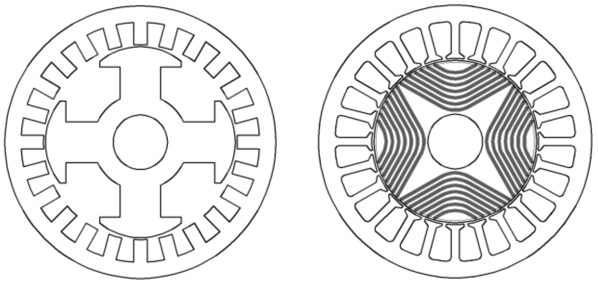
Brushed electrical machines include DC, wound field synchronous and wound rotor induction machines. However, brushed electrical machines require regular maintenance and hence less suitable for modern HEVs/EVs. Only the wound field synchronous machine is used in very limited EVs, such as Renault Fluence and ZOE [8]. Hence, in this paper, the DC and wound rotor induction machines are not included for further discussion.

Brushless electrical machines have more varieties and are more suitable for HEVs/EVs. Induction and permanent machines currently are the two dominating machines for HEVs/EVs. Synchronous reluctance machines (SynRMs) are also attracting increasing attention for HEVs/EVs, which will be shown later. For switched reluctance (SR) machines, automotive companies have made several attempts to use these motors for EV propulsion starting from early 1990s [10]. The latest development of SR machine for HEV/EV applications can be found in [20-23]. However, even after experiencing the extremely high price of rare-earth PM, SR machines are still not widely employed in HEVs/EVs. It is mainly due to the inherent disadvantages of high torque ripple, acoustic noise and vibration, low overload capability and non-standard drivers. Hence, SR machine is not included for further investigation in this paper. Except these conventional topologies, VFRM is another type of brushless electrical machines and could be suitable for HEV/EV applications. PM-assisted synchronous reluctance machine (PM-assisted SynRM) is a new type IPM machine with the output mainly contributed by the synchronous reluctance torque. Due to the benefit of low cost, PM-assisted SynRM has gained worldwide attention for HEV/EV applications.

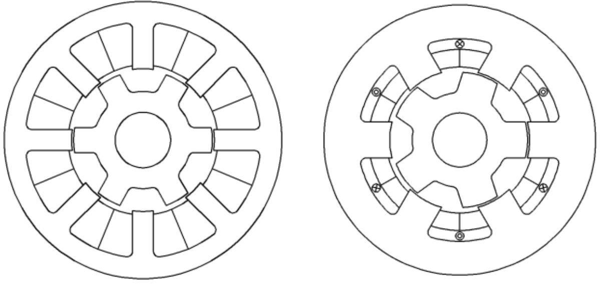
Therefore, in following sections, PM, induction, wound field synchronous, synchronous reluctance, variable flux reluctance, and PM-assisted synchronous reluctance machines are selected for further quantitative comparison. Since currently the IPM machine is most widely used for HEV/EV applications, it is chosen as the benchmark for the quantitative comparison.



(a) Induction (b) Permanent magnet



(c) Wound field synchronous (d) Synchronous reluctance



(e) Switched relectance (f) VFRM

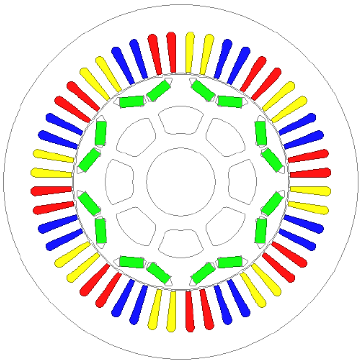
Fig. 2. Cross-sections of different electrical machines.

IV. PERMANENT MAGNET MACHINE

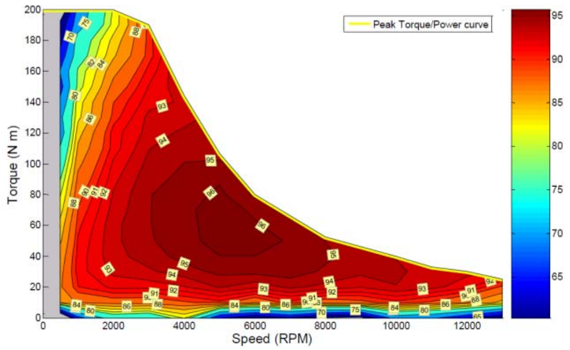
PM machines are excited by PM and have a large number of configurations, such as radial field/axial field/transverse flux, distributed/concentrated windings, integral/fractional slot, rotor/stator located PMs, as well as surface-mounted/inset/interior [3-4]. In this paper, the PM machine is referred to the most widely used configuration for HEV/EV traction applications which has radial field, distributed windings, integral slot and IPM rotor.

For HEV/EV traction applications, the main advantages of PM machines are: (1) high torque and power densities and hence light weight and smaller volume; (2) high efficiency; (3); high power factor; (4) good heat dissipation since the heat mainly arises in the stator; (5) various configurations and adjustable performance; and (6) quick acceleration due to lower electromechanical time constant of the rotor. The main disadvantages include: (1) relatively high cost and uncertainty due to rare earth PM; (2) relatively difficult on flux weakening especially when the electric loading is limited; (3) Relatively lower efficiency at high speed due to additional current component required for flux weakening; (4) the risk of irreversible demagnetization of PM due to high temperature, high demagnetizing armature field or vibration; and (5) high back EMF at high speed under in case of fault.

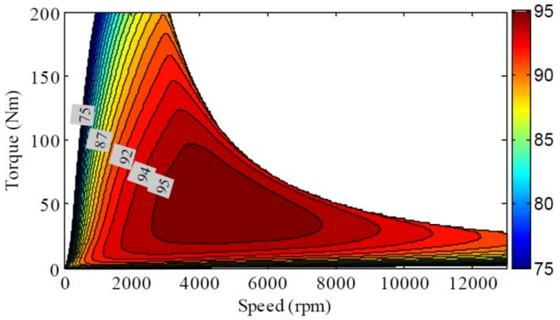
Their typical constant power range can be 3-4 times of base speed, which is suitable for EV applications. For the light-duty EV, almost the entire industry has shifted to PM machines even after experiencing the high price of rare-earth PM [6]. Amongst PM machine based HEVs/EVs, Prius is the most popular. Hence, its later design Prius 2010 IPM machine is selected as the benchmark. It is also due to the fact that its detailed specification and performance can be found publically in [24]. The cross-section and specification of Prius 2010 IPM machine are given in Fig. 3 and TABLE I. All the other types of electrical machines are designed and optimized using the same specification listed in Table 1 and then compared with Prius 2010 IPM machine in the following sections individually. The further synthetic comparison between the most promising machines is carried out afterwards.



(a) Cross-section



(b) Measured efficiency map [24].



(c) Predicted efficiency map [25].

Fig. 3. Cross-section and efficiency map of Prius 2010 IPM machine

TABLE I
MAIN PARAMETERS OF PRIUS 2010 IPM MACHINE [24]

Parameters	value	Parameters	value
Stator outer diameter	264mm	Max. DC bus voltage	650V
Stack length	50.5mm	Max. phase current	225A$_{peak}$
Airgap length	0.73mm	Stator inner diameter	161.9mm
Number of slots	48	Packing factor	0.465
Number of poles	8	Turns per phase	88
Maximum speed	14000	Slot opening	1.88mm

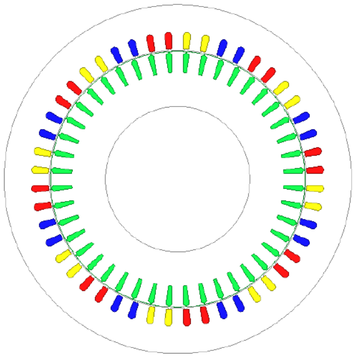
V. INDUCTION MACHINES

Induction machine relies on the eddy current in the rotor conductor. IM is the most mature and still the main workhorse for various industrial applications. IM is also widely used for HEVs/EVs, especially in early designs.

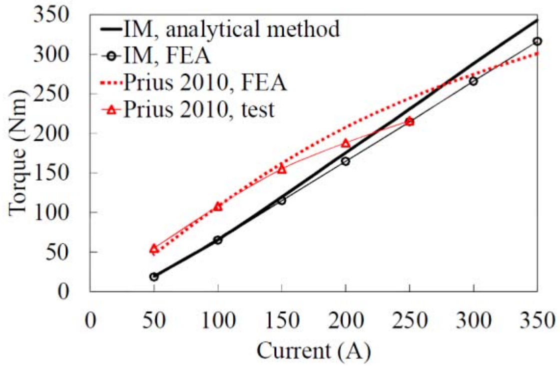
For HEV/EV traction applications, the main advantages of IM include: (1) robust structure; (2) relatively low cost; (3) well established manufacturing techniques; (4) reliable; (5) comparatively good efficiency at high speed; (6) good overload or peak torque capability, and (7) good dynamic performance which can be achieved by for example vector control and direct torque control. The disadvantages include: (1) For conventional IMs, the constant power range typically extends to 2–3 times the base speed. But in HEV/EV machines, it requires an expansion of 3 times above the base one. Hence, the design of IM is more complicated to satisfy the HEV/EV demand. (2) The efficiency is generally lower than a PM machine due to the inherent rotor loss. For the same reason, the size of an induction machine is generally bigger than a PM machine with the same power and speed rating although it depends on the requirement of peak torque. (3) Low power factor and low inverter-usage factor. (4) The heat on the rotor is more difficult to be dissipated. (5) The control schemes are a little difficult due to the variable equivalent parameters.

For HEV/EV traction applications, IM has to be specially designed to achieve wider constant power speed range. The peak efficiency may need to be sacrificed to obtain a better performance curve over a wider speed range. The major design parameters for IMs include the number of poles, the number of stator and rotor slots, the shape of the stator and rotor slots, and the winding disposition, which determine the IM topologies. The general sizing of IM is discussed in [26]. The prediction of torque-speed envelope of IMs by analytical method is presented in [27] and the influence of design parameters on the flux weakening performance of IM is investigated in [28]. In order to improve the efficiency, it is preferred to use copper rotor IMs.

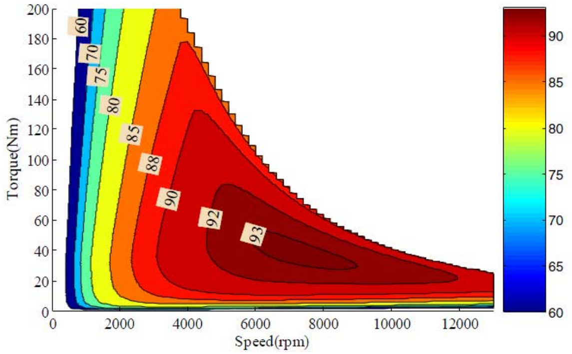
In [18], the performance of aluminum rotor IM, SPM and IPM machines are compared based on analytical and finite element analyses. In [19], the copper rotor IM is compared with the Prius 2004 IPM machine having the same outer diameter, cooling system, continuous torque and performance envelop. The comparison between both aluminum and copper rotor IMs with an IPM machine based on the Prius 2010 specification is presented in [29]. The overload capability, torque/power-speed curves, power factor, torque ripple, efficiency map and material cost are quantitatively compared. The overload capability and efficiency maps are illustrated in Fig. 4. It can be seen that due to the better overload capability, the IMs actually can achieve a competitive maximum torque with the IPM machine although the torque capability of IMs at the electrical load of continuous operation (rated load) is much lower. The maximum efficiency of IM machine is approximately 3-4% lower than the IPM machine.



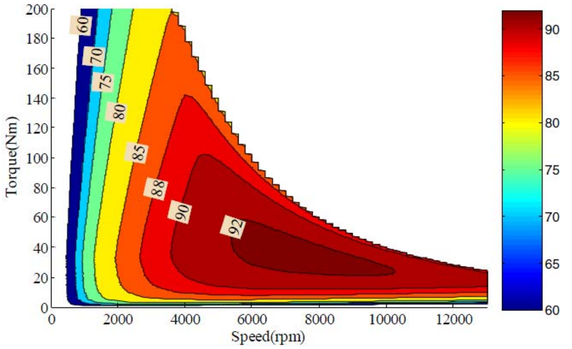
(a) Cross-section of IM



(b) Max. average torque with current amplitude



(c) Efficiency map of copper rotor IM



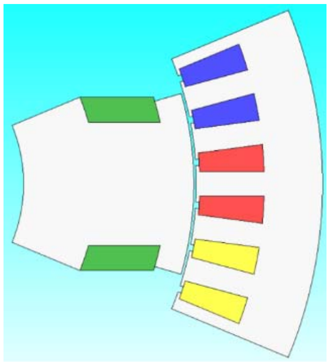
(d) Efficiency map of aluminum rotor IM

Fig. 4. Comparison of aluminium and copper rotor IMs with IPM based on Prius 2010 specification [29].

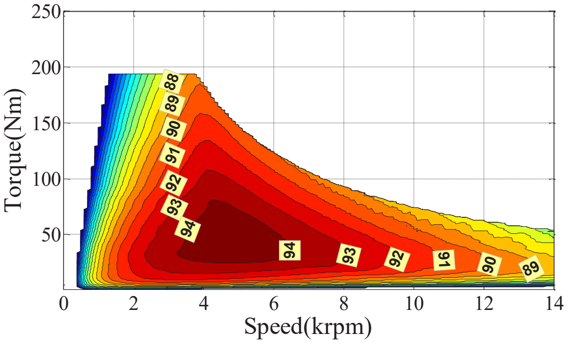
VI. WOUND FIELD SYNCHRONOUS MACHINES

Wound field synchronous machine is an old technology [30]. It is very popular for high power generation applications. For EV applications, wound field synchronous machines produced by Continental Group are used for Renault's middle-size EVs [8]. The main advantage of this machine is that the excitation field can be regulated easily. Thus, the constant power speed range is much wider (more than 5 times) and the efficiency at partial load can be improved. The major disadvantages of wound field synchronous machines are: (1) Brushes and slip ring makes the machine bigger and need maintenance. (2) The copper loss in the rotor, which is also much more difficult to be cooled.

In [31] and [32], the designs of wound field synchronous machines for EV applications are discussed. In [33], the prediction method and characteristics of the efficiency map of wound field synchronous machine are presented and analysed. The comparison between wound field machine and IPM machine based on the Prius 2010 specification is carried out in [34]. Both machines have the same outer diameter, effective axial length, total copper loss, airgap length, slot and pole numbers, maximum DC bus voltage and number of turns per phase. The relevant results are shown in Fig. 5. It shows that the wound field synchronous machine has around 2% lower maximum efficiency and 5% lower maximum torque than the IPM machine. Please note that almost half of the copper loss in wound field synchronous machine is in the rotor which is much more difficult to be dissipated. It is worth mentioning that the influence of the brushes and slip ring is not considered.



(a) Cross-section of wound field synchronous machine



(b) Efficiency map of wound field synchronous machine

Fig. 5. Comparison of wound field synchronous machine with IPM machines based on Prius 2010 specification [34].

VII. SYNCHRONOUS RELUCTANCE MACHINES

SynRM employs a distributed stator winding identical to that of an IM and uses vector control to achieve the high performance. Its rotor may be similar to that of a SR machines with salient structure or to the IPM rotor but without PMs. In order to increase the saliency ratio, it is preferable to employ a multi-layer reluctance rotor, or even axially laminated rotor.

For HEV/EV traction applications, the major advantages of SynRM are: (1) robustness, (2) relative cheaper and (3) failure safe at high speed. The main disadvantages are: (1) poor torque and overload capability since the saliency ratio reduces significantly as the magnetic saturation increases; (2) low power factor; and (3) high ripple torque resulting in higher noise and vibrations.

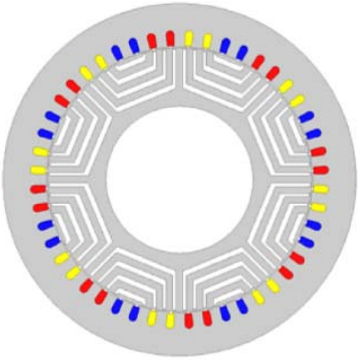
Although it has not been used in EVs, SynRM has gained attention due to the concern of price increase or shortage of rare earth PM materials. Recently, ABB has advanced this technology and already commercialized for several industrial applications to replace IMs [35]. SynRM is also one of the popular research topics for electric drives. In [36], new operation diagram and parameter estimator are developed. In [37], optimal slot/pole and flux-barrier layer number combinations are investigated. A methodology for sizing a SynRM is presented in [38]. Multi-objective optimization is discussed in [39]. The optimal barrier shape is investigated in [40]. The torque ripple reduction methods are discussed in [41] and [42]. In [43], the performance of different types of SynRMs is compared. SynRM with concentrated windings is investigated in [44]. The influence of magnetic saturation is studied in [45].

The comparison between SynRM and IPM machine based on the Prius 2010 specification is reported in [25]. All machines have the same stator outer diameter, stack length, airgap length, total copper loss and voltage. The cross-section and efficiency map of SynRM are shown in Fig. 6. It can be seen that SynRM has 20% lower maximum torque and 3-4% lower maximum efficiency than the IPM machine.

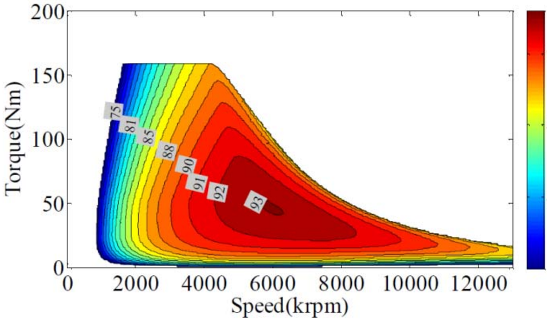
VIII. PM-ASSISTED SYNCHRONOUS RELUCTANCE MACHINE

With less torque contribution from the PM, more torque should be produced by reluctance torque. Hence, this type of machine is very often called PM-assisted SynRM but still a type of PM machine. The PM in PM-assisted SynRM can be either ferrite or smaller amount of rare-earth magnet. An early attempt to use PM-assisted SynRM for EV can be found in [46]. The torque ripple reduction is discussed in [41]. Optimal amount of PM is investigated in [47]. The performance when using fractional slot configuration is analysed in [48]. Latest developments on the design and modelling of PM-assisted SynRM can be found in [45] and [49-53]. For actual applications, BMW i3 uses PM-assisted SynRM. Brusa of Switzerland has demonstrated a version of PM-assist SynRMs for EV applications [10].

Comparison between PM-assisted SynRM with IPM machine based on Prius 2010 specification is also conducted in [25]. All machines have the same stator outer diameter, stack length, airgap length, total copper loss and voltage. The cross-sections and efficiency maps of PM-assisted SynRMs are shown in Fig. 7. It can be seen that with the aid of ferrite or a small amount of NdFeB, PM-assisted SynRMs can obtain a similar maximum torque and a slightly lower (<1%) maximum efficiency than the IPM machine.

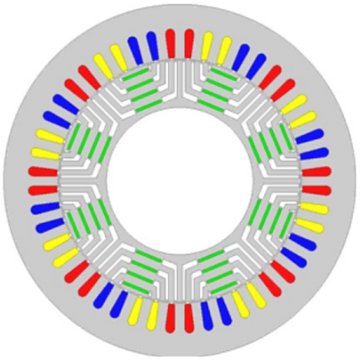


(a) Cross-section of SynRM

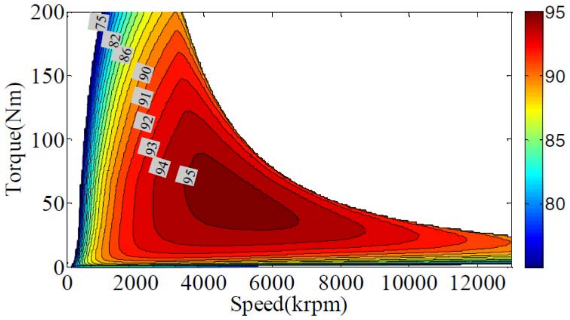


(b) Efficiency map of SynRM

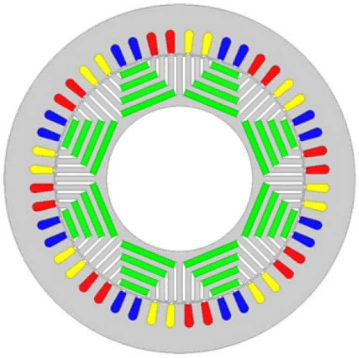
Fig. 6. Comparison of SynRM with IPM machines based on Prius 2010 specification [25].



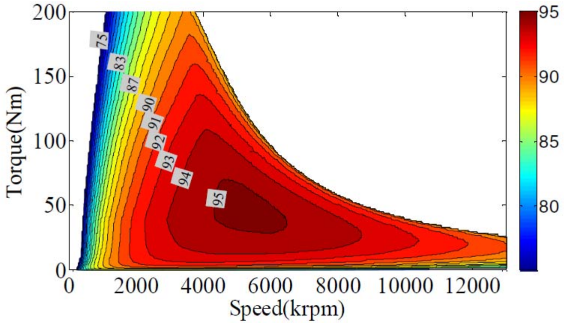
(a) Cross-section of NdFeB-assisted SynRM



(b) Efficiency map of NdFeB-assisted SynRM



(c) Cross-section of ferrite-assisted SynRM



(d) Efficiency map of ferrite-assisted SynRM

Fig. 7. Comparison of PM-assisted SynRM with IPM machines based on Prius 2010 specification [25].

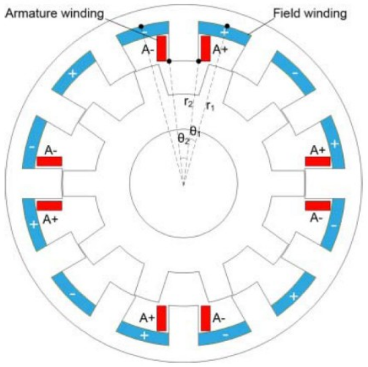
IX. VARIABLE FLUX RELUCTANCE MACHINE

More recently, a novel PM free electrical machine called variable flux reluctance machine (VFRM) is developed [54-59]. Its typical cross-section is shown in Fig. 2(f). VFRMs have doubly salient stator and rotor and the rotor does not have any PM or winding, which is the same to SR machines. Instead of single set of three-phase windings in SR machines, VFRM has two sets of windings on the stator, namely the DC excitation and AC armature windings. Both windings are concentrated wound on each stator poles. Being different from SR machines, the AC armature windings are supplied with sinusoidal three-phase currents. Consequently, VFRMs have all advantages of SR machines while having much lower noise and vibration [60] and driven by conventional three-phase inverters. Furthermore, for VFRMs, they can have odd rotor pole numbers while for SR machines their rotor pole number must be even. Meanwhile, VFRM machines having odd rotor pole number exhibit sinusoidal back EMFs and higher torque density than VFRM machines having even rotor pole number [57, 58, 61, 62]. By using open-winding method, the DC and AC windings can be merged into one single set winding and the driving current has DC biased sinusoidal waveform [63, 64].

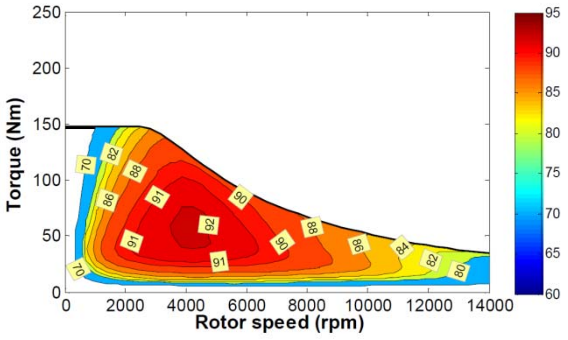
Due to these advantages, VFRM has attracted attentions. Some of the latest publications can be found in [65-69]. In [70], the investigation is carried out together with Toyota and the work in [71] is cooperated with GE.

The comparison between VFRM and IPM machine based on the Prius 2010 specification is carried out in [72] with either the same stack length or total axial length including end windings.

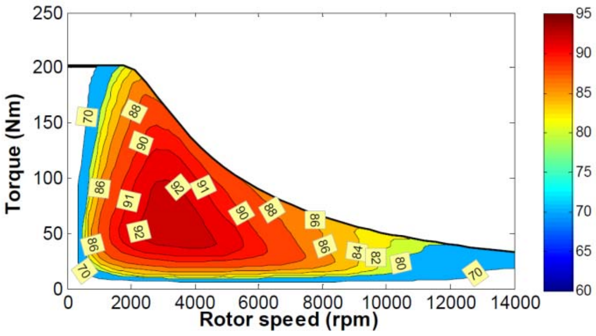
The outer diameter, voltage and current limits are also the same. The cross-section and efficiency maps of VFRM are shown in Fig. 8. Under the same stack length (50.8mm), the VFRM design has 25% lower maximum torque and around 4% lower maximum efficiency than the IPM design. By taking advantage of the concentrated winding configuration, the stack length of VFRM can be increased to 70.8mm while the total axial length remains the same of IPM design. In this case, VFRM can achieve similar maximum torque with the IPM machine. However, the efficiency remains lower.



(a) Cross-section of VFRM



(b) Efficiency map of VFRM with same stack length



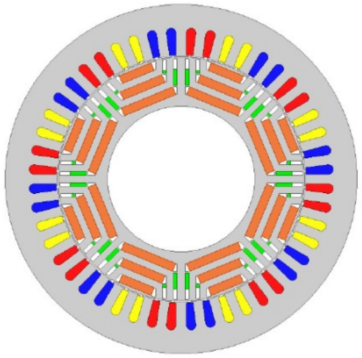
(c) Efficiency map of VFRM with same total axial length

Fig. 8. Comparison of VFRM with IPM machines based on Prius 2010 specification [72].

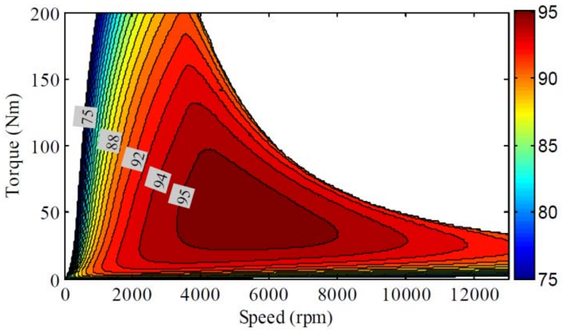
X. SYNTHETIC COMPARISON

In previous sections, the other five types of electrical machines have been quantitative compared with the IPM machine individually. Since all these comparisons are carried out on the same specification, it is then possible to further compare these electrical machines synthetically. However, in order to show the results more clearly and reduce the calculation load, only the most promising electrical machines are selected for the synthetic comparison.

IPM machine and IM are the most widely used in actual HEVs/EVs. Also, PM machine also has the highest torque density and maximum efficiency. IM is currently the cheapest and exhibits high peak torque. According the quantitatively comparison in previous sections, PM-assisted SynRMs are the most promising alternatives to IPM machines due to the competitive performance and lower cost. Wound field synchronous machine, SynRM, and VFRM have much reduced torque capability and efficiency than IPM design. Therefore, IPM machine, IM, PM-assisted SynRM are selected for the further synthetic comparison. Except NdFeB- and ferrite-assisted SynRMs, hybrid PM-asissted SynRM is also added for this synthetic comparison. Its cross-section and efficiency map are shown in Fig. 9. SynRM is included as well for the sake of better understanding the benefits of PM excitation in PM-assisted SynRM.



(a) Cross-section of hybrid PM-assisted SynRM



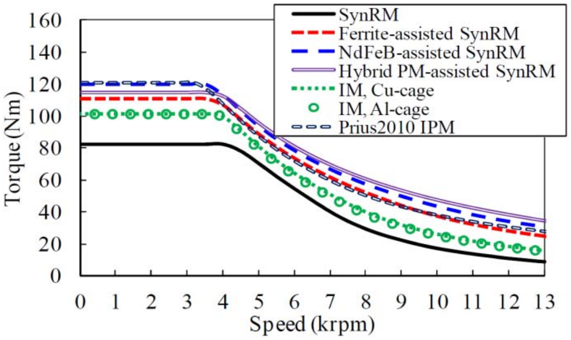
(b) Efficiency map of hybrid PM-assisted SynRM

Fig. 9. Comparison of hybrid PM-assisted SynRM with IPM machines based on Prius 2010 specification.

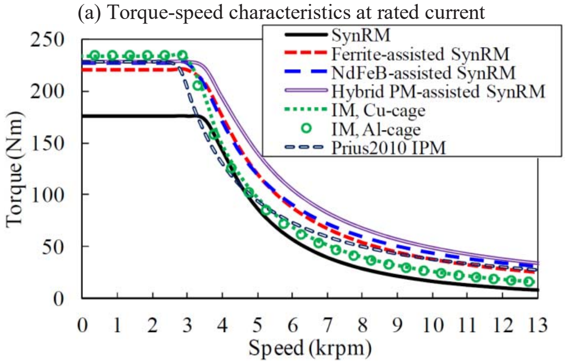
In order to provide a comprehensive comparison, torque/power-speed characteristics, power factor along the torque-speed characteristics, efficiency maps, as well as overall efficiencies for different drive cycles are investigated. The efficiency maps for all investigated machines have been shown in Figs. 3-9. The torque/power-speed characteristics, power factor along the torque-speed characteristics, as well as overall efficiencies for different drive cycles are compared in Figs. 10-13, respectively. From Fig. 10, it can be seen that SynRM has the lowest torque density and the worst constant power speed range (CPSR). All PM-assisted SynRMs have competitive torque capability and CPSR with the IPM machine. For IMs, although it has lower maximum torque than the IPM machine at the rated current, it has even slightly higher maximum torque than the IPM machine at the maximum current. It is due to that IM has better overload capability as shown in Fig. 4(b). However, the CPSR of IM is still much worse than that of the IPM machine. From Fig. 11, it can be seen that SynRM has the lowest power factor. IMs have the second lowest power factor. PM-assisted SynRMs have competitive power factor with the IPM machine.

Based on the efficiency maps, the drive cycle based overall efficiencies, which are more useful than the maximum efficiency for actual operations, can be calculated and compared in Figs. 12 and Fig. 13. Two types of drive cycles are considered. The New Europe Drive Cycle (NEDC) operates more frequently in low torque and speed region and the ARB operates more frequently in the higher torque and speed region.

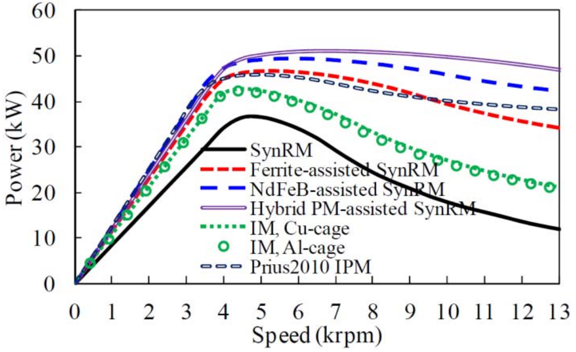
For the overall efficiency based on NEDC, the IMs are the lowest. The SynRM is better than IMs less than 1%. The IPM machine and PM-assisted SynRMs have more than 10% higher overall efficiency than the IMs. The NdFeB- and hybrid PM-assisted SynRM even have slightly higher overall efficiency than the IPM machine.



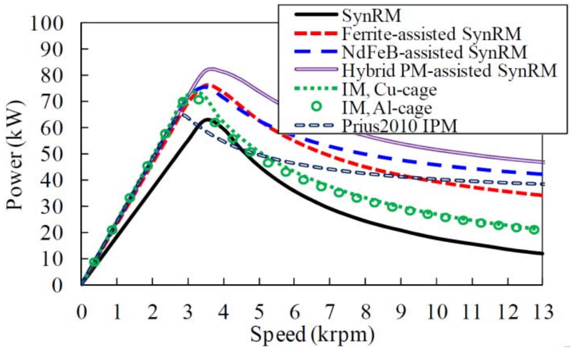
(a) Torque-speed characteristics at rated current



(b) Torque-speed characteristics at maximum current

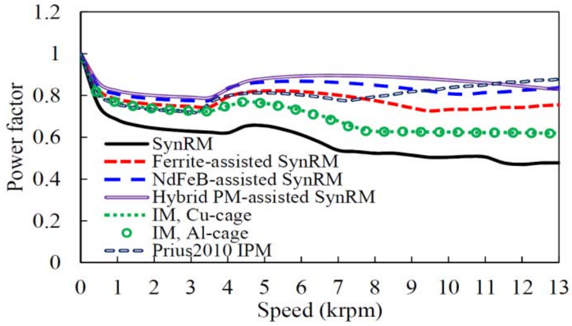


(a) Power-speed characteristics at rated current

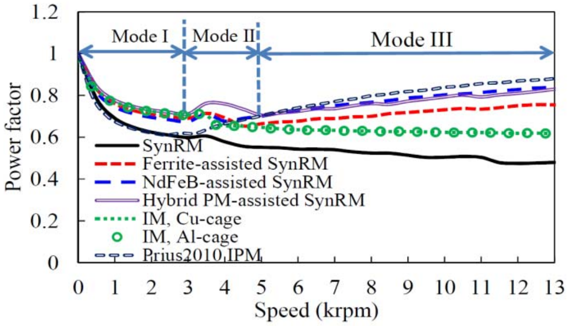


(b) Power-speed characteristics at maximum current

Fig. 10. Comparison of torque/power-speed characteristics.



(a) At rated current

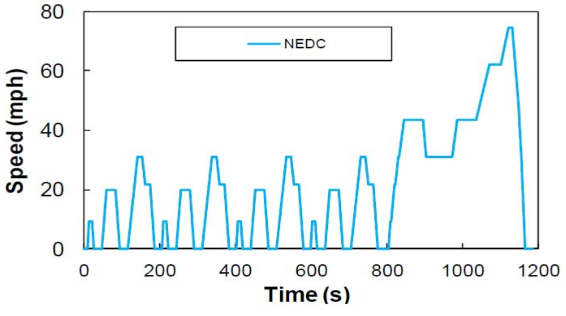


(b) At maximum current

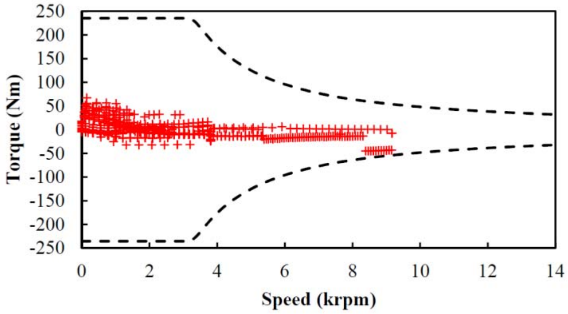
Fig. 11. Comparison of power factor along torque-speed characteristics.

For the ARB based result in Fig. 13(c), the SynRM has the lowest overall efficiency. The IMs have around 3% higher efficiency than the SynRM. The efficiency is further increased by 14-15% when using ferrite-SynRM or IPM machine. The hybrid PM-assisted SynRM has the highest overall efficiency which even is 8% higher than the IPM machine. The NdFeB-assisted SynRM machine also has 5% higher overall efficiency than the IPM machine.

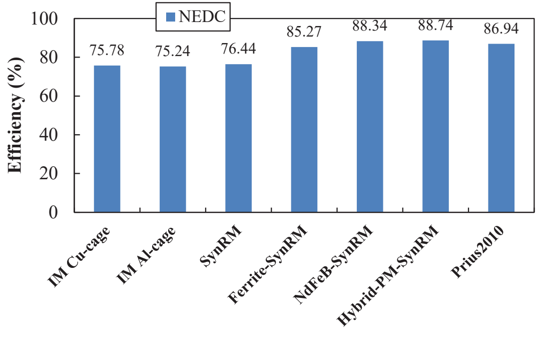
Therefore, it can be concluded that PM-assisted SynRM is the most promising alternative for IPM machine due to lower cost and potentially higher overall efficiency.



(a) NEDC

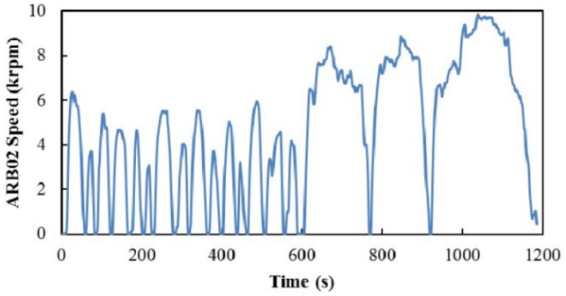


(b) Torque-speed distribution of NEDC

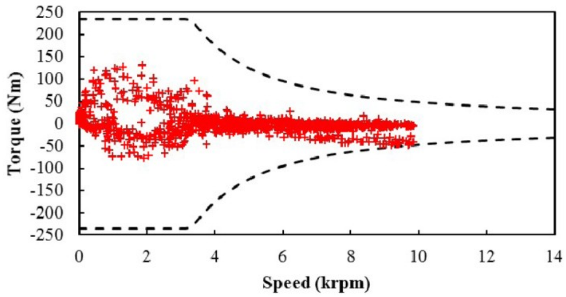


(c) Overall efficiency

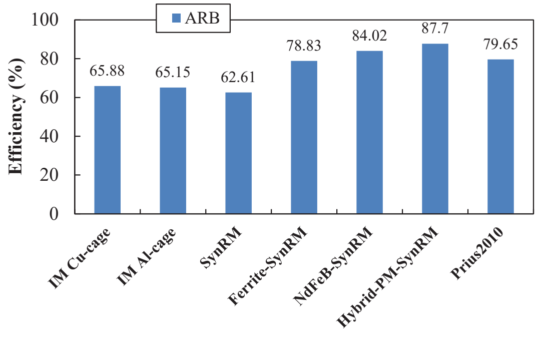
Fig. 12. Comparison on overall efficiencies for NEDC.



(a) ARB



(b) Torque-speed distribution of ARB



(c) Overall efficiency

Fig. 13. Comparison on overall efficiencies for ARB.

XI. CONCLUSION

In this paper, the major types of electrical machines for HEV/EV traction applications are comprehensively reviewed and quantitative compared based on the same specification. It is found that IPM machines have much better overall power factor and efficiency than IMs. PM-assisted SynRMs are identified as the most promising alternatives to IPM machines due to the benefits of lower cost and potentially higher overall efficiency. Although IMs have lower efficiency, they are still competitive due to low cost and better overload capability. Wound field synchronous machine, SynRM and VFRM are currently less attractive for HEV/EV tractions due to lower torque density and efficiency.

It is worth mentioning that in the comparison of this paper, only basic electromagnetic performances are compared, there are no considerations of thermal and mechanical aspects, which are clearly also very important and will significantly affect the qualitative results. Further, it is worth mentioning that there are a lot of newly developed novel electrical machine technologies and topologies, most notably, hybrid excited PM machines, stator-PM machines, Vernier machines, and magnetically geared machines etc. However, currently they are either too complicated in structure, or have low rated and/or peak torque density, or poor flux weakening capability, or low power factor, preventing their application in commercial EVs/HEVs although they are under extensive research and development.

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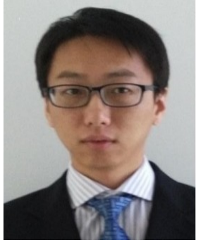
Professor Z. Q. Zhu , born on 23 Sept. 1962, Fellow of Royal Academy of Engineering, Fellow IEEE, Fellow IET, PhD, Professor at The University of Sheffield, UK. Major research interests include design, control, and applications of brushless permanent magnet machines and drives for applications ranging from automotive to renewable energy.

W. Q. Chu received the B. Eng. and M. Sc. degrees in electrical engineering from Zhejiang University, Hangzhou, China in 2004 and Huazhong University of Science and Technology, Wuhan, China in 2007, respectively, and the Ph.D. degree in the electronic and electrical engineering from The University of Sheffield, UK, in 2013.

From 2007 to 2009, he was with Delta Electronics (Shanghai) Co. Ltd. From 2012 to 2014, he was a postdoctoral research associate with The University of Sheffield. Currently, he is a principal design engineer with CRRC Electric Drive Technology Research Centre, The University of Sheffield, UK. His major research interests include electric machines and applications.



Y. Guan received the B.Eng. and M.Sc. degrees from Zhejiang University, Hangzhou, China, in 2006 and 2008, respectively, and the Ph.D. degree from The University of Sheffield, Sheffield, U.K., in 2015, all in electrical and electronic engineering.

From 2008 to 2011, he was an Engineer with Sany Electrics Co. Ltd., Beijing, China. Since 2014, he has been a Research Associate with The University of Sheffield, Sheffield, U.K. His research interests include the design and analysis of permanent-magnet and induction machines, and superconducting generators.